Recent ATLAS measurements of azimuthal anisotropies in $pp$ and $p+Pb$ collisions

Adam Trzupek$^1$* on behalf of the ATLAS Collaboration

$^1$Institute of Nuclear Physics PAS, ul. Radzikowskiego 152, 31-342 Kraków, Poland

Abstract. The azimuthal anisotropies of particle yields observed in relativistic heavy-ion collisions are considered as an evidence of the formation of a deconfined Quark-Gluon Plasma produced in these collisions. Interestingly, recent measurements in $pp$ and $p+Pb$ systems from ATLAS and other experiments show similar features as those observed in A+A collisions, indicating the possibility of the production of such a deconfined medium in smaller collision systems. This report presents a summary of the recent ATLAS results on azimuthal anisotropies in $pp$ collisions at 5.02 TeV and 13 TeV, $p+Pb$ collisions at 5.02 TeV and 8.16 TeV as well as in peripheral 2.76 TeV Pb+Pb interactions. It includes measurements of two-particle correlations of charged particles as well as correlations of heavy flavor muons and charged particles in $\Delta \phi$ and $\Delta \eta$, with a template fitting procedure used to subtract the dijet contributions. Additionally, measurements of cumulants of multi-particle correlations, $c_n(2–8)$ are presented. The two-particle correlations and cumulants confirm a presence of collective phenomena in these collision systems, but the results on four-particle cumulants for $pp$ collisions do not demonstrate a similar collective behaviour. However, the cumulant measurements in small collision systems can be biased by non-flow correlations. A novel subevent cumulant method that suppresses the contribution of non-flow effects was proposed recently by ATLAS allowing to measure significant azimuthal anisotropies in both $pp$ and $p+Pb$ collisions.

1 Introduction

One of the main signatures of the formation of strongly interacting Quark-Gluon Plasma (QGP) in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) is the large azimuthal anisotropy of produced particles [1, 2]. Interestingly, significant azimuthal anisotropy was also observed (at the LHC for the first time) in $pp$ and $p+Pb$ collisions [3, 4]. Since the first measurements, the collective phenomena in small systems are under extensive theoretical and experimental study, which significantly improves our understanding of the flow phenomena in heavy-ion collisions. However, there are still open questions such as what is the underlying mechanism for the observed correlations, what is the role of initial effects or whether the QGP exists in collisions involving light nuclei. In this report, the recent ATLAS [5] results on Fourier coefficients $v_n$ of charged-particle azimuthal distributions, extracted from the two-particle correlations using a novel template fitting method, are shown for $pp$ collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV and $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV [6] and $\sqrt{s_{NN}} = 8.16$ TeV [7]. The template fitting method was also used

*e-mail: adam.trzupek@ifj.edu.pl
Recently, a two-particle correlation analysis was performed by ATLAS [6, 7, 13] for high multiplicity events of $N_{ch}^{rec} \geq 120$. The plots are for charged particles of $0.5 < p_T^{ab} < 5$ GeV. The distribution has been truncated to suppress the peak at Δη = Δφ = 0 [4].

![Figure 1](image1.png)

Figure 1. Two-particle correlation functions $C(Δη, Δφ)$ in 13 TeV pp collisions corresponding to multiplicity range of $N_{ch}^{rec} \geq 120$. The plots are for charged particles of $0.5 < p_T^{ab} < 5$ GeV. The distribution has been truncated to suppress the peak at Δη = Δφ = 0 [4].

To obtain $v_2$ of muons from heavy-flavor hadron decays in $p+Pb$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV [7]. For the small collision systems and additionally for low-multiplicity $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions, the measurements of multi-particle cumulants and corresponding flow harmonics are also presented [8, 9].

2 Two-particle correlations

The two-particle correlation technique [3, 4] is deployed to measure the azimuthal anisotropy in small systems and is also commonly applied to probe collective phenomena in heavy-ion collisions [10–12]. Recently, a two-particle correlation analysis was performed by ATLAS [6, 7, 13] for pp collisions at $\sqrt{s} = 2.76$ TeV, 5.02 TeV and 13 TeV, and for $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 8.16 TeV. For low-multiplicity pp or $p+Pb$ collisions, the correlation function measured in the relative pseudorapidity (Δη) and azimuthal angle (Δφ) of two charged particles with transverse momenta $p_T^a$ and $p_T^b$, is dominated by non-flow effects due to jet production, momentum conservation, resonance decays or Bose-Einstein correlations. The correlation function features a sharp peak centered at $(Δφ, Δη) = (0, 0)$ and a broad, extended in Δη structure at $Δφ \approx π$. In high-multiplicity collisions, see Figure 1, an additional long-range structure in Δη at $Δφ \approx 0$, called “near-side ridge”, is clearly visible. Also the correlation function at $Δφ \approx π$ is broadened relative to low-multiplicity collisions, revealing a presence of the “away-side ridge”. The strength of the ridge correlations is commonly quantified by the “per-trigger yield”, $Y(Δφ)$, which measures the average number of particle pairs associated with a trigger particle with $p_T^a$ at the large pseudorapidity separation, $|Δη| > 2$, imposed to suppress the non-flow correlations. Using a template fitting function, the per-trigger yield is separated into two components: a scaled per-trigger yield for low-multiplicity interactions, $Y^{periph}(Δφ)$, describing the back-to-back jet correlations, and an azimuthal modulation term describing the ridge, see Figure 2. In this approach, the non-flow correlations are described by the fit function, therefore, there is no need to perform the “peripheral subtraction” procedure on $Y(Δφ)$ or $Y^{periph}(Δφ)$, which has been commonly used in other analyses. In the peripheral subtraction procedure the non-flow effects are suppressed by setting the $Y$ pedestal level by a zero-yield at minimum (ZYAM) [6]. The azimuthal modulation...

![Figure 2](image2.png)

Figure 2. Template fits to the per-trigger particle yields $Y(Δφ)$, in 13 TeV pp collisions for high multiplicity events of $N_{ch}^{rec} \geq 120$. The solid points indicate the measured $Y(Δφ)$, the open points and curves show different components of the template fit [4].
amplitudes $2v_{n,n}$ obtained from the fitting procedure were found to factorize into a product of single particle flow harmonics $v_n \cdot v_n$, hence the flow harmonics are obtained from the formula: $v_n = \sqrt{v_{n,n}}$. A weak variation of $v_{n,n}$ on the applied pseudorapidity $|\Delta\eta|$ cut was observed. Figure 3 (the left column) shows measurements of $v_2$, $v_3$ and $v_4$ harmonics in 5.02 TeV and 13 TeV $pp$, and 5.02 TeV and 8.16 TeV $p+Pb$ collisions as a function of the number of charged particles with $p_T > 0.4$ GeV and $|\eta| < 2.5$, $N_{ch}^{rec}$. One can see that all three $v_n$ harmonics in 5.02 TeV and 13 TeV $pp$ data are $N_{ch}^{rec}$-independent, while the $p+Pb$ $v_2$, $v_3$ and $v_4$ increase with increasing event multiplicity, except for $v_2$, which starts to be multiplicity independent for $N_{ch}^{rec} > 150$. Figure 3 also shows a comparison of the $v_2$ harmonic measured in $p+Pb$ at $\sqrt{s_{NN}} = 8.16$ TeV to those measured at $\sqrt{s_{NN}} = 5.02$ TeV. The $v_2$ harmonics at the two collision energies are consistent within the systematic uncertainties.

Figure 3 (the right column) shows the $p_T$ dependence of $v_n$ in 5.02 and 13 TeV $pp$, and 5.02 TeV $p+Pb$ collisions for $N_{ch}^{rec} \geq 60$. Similar $v_2$ harmonics are observed in $pp$ collisions at both collision energies. With increasing transverse momentum, $v_2$ harmonics rise reaching a maximum near 3 GeV and then drop, reaching almost 0 at $p_T \approx 7$ GeV. A more rapid increase of $v_2$ is observed in $p+Pb$ collisions, but generally a similar trend is preserved in both systems. The $v_3$ harmonics in 13 TeV $pp$ collisions increase with increasing $p_T$ over the measured transverse momentum range. For $p+Pb$ collisions...
collisions, larger $v_3$ values are measured than in $pp$ for $p_T < 3$ GeV. At higher $p_T$, $v_3$ in $p+Pb$ data saturates. The $v_4$ harmonics in 13 TeV $pp$ and 5.02 TeV $p+Pb$ collisions increase with increasing transverse momentum and larger $v_4$ values are measured in $p+Pb$ than in $pp$ collisions.

3 Correlations between muons and charged-particles

Charm and bottom quarks provide an important signature of the QGP formed in ultra-relativistic heavy ion collisions [14]. It is expected that at high transverse momenta, $p_T \gg 5$ GeV, heavy quarks produced in the early stage of the collision lose energy in the QGP with mass-dependent modifications [15]. At lower transverse momenta, $p_T \lesssim 5$ GeV, the quarks are expected to interact with the hot and dense medium acquiring an azimuthal anisotropy due to the collective expansion of the QGP. Measurements of heavy flavor quarks in A+A collisions were performed at RHIC and LHC [16–18]. A significant suppression of heavy quarks production due to energy loss was observed as well as a significant azimuthal anisotropy was measured.

Recently, ATLAS performed a measurement of the long-range correlations between reconstructed muons of $4 < p_T^\mu < 8$ GeV and inclusive charged particles in $p+Pb$ collisions at $\sqrt{s} = 8.16$ TeV [7]. Majority of prompt muons at low transverse momenta, $p_T \lesssim 5$ GeV, results from decays of heavy-flavor hadrons containing charm or bottom quarks [19]. Therefore, if a QGP is formed in $p+Pb$ collisions, its collective expansion may influence heavy-flavor hadron production [20], which can be probed by the measurement of two-particle correlations.

Based on a Monte Carlo simulation of the ATLAS detector [7], it was found that the sample of reconstructed muons with $4 < p_T < 8$ GeV is contaminated up to 45% by background muons originating from pion and kaon decays, muons produced in hadronic showers, and mis-associations of Inner Detector (ID) and Muon Spectrometer (MS) tracks. To lower the background fractions, the momentum imbalance, $\Delta p/p_{ID} = (p_{ID} - p_{MS})/p_{ID}$, is calculated for each muon, where $p_{ID}$ and $p_{MS}$ are the reconstructed muon momenta measured in the ID and MS, respectively. As the momentum of background muons measured in the MS is typically lower than the momentum measured in the ID, majority of background muons are characterised by the positive momentum imbalance, $\Delta p/p_{ID} > 0$. Therefore, only muons with $\Delta p/p_{ID} < 0$ are accepted for the correlation measurement. This require-
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The two-particle correlations of reconstructed muons and charged particles (h − μ), obtained in a similar way as the two-particle correlations for inclusive charged particles (h − h), show a clear ridge structure in the high-multiplicity 8.16 TeV p+Pb collisions. To extract the muon-v$_2$, the two-particle correlation template fitting method, described in Section 2, is used. Figure 4 shows the measured muon-v$_2$ obtained from h−μ correlations of 4 $< p_T^h < 6$ GeV and 0.5 $< p_T^μ < 5$ GeV as well as charged-particle v$_2$ obtained from h−h correlations of 0.5 $< p_T^{ch} < 5$ GeV. Within systematic uncertainties, the muon-v$_2$ remains constant over the measured N$_{ch}^{rec}$ range, and is smaller than v$_2$ for charged particles. However, it should be noted that different p$_T$ ranges are used for both measurements. Figure 5 shows the p$_T$ dependence of the muon-v$_2$ over transverse momentum range 4 $< p_T^h < 8$ GeV measured for large multiplicity events of N$_{ch}^{rec}$ ≥ 100. A decrease of muon-v$_2$ is observed with increasing p$_T$.

### 4 Multi-particle cumulants

A commonly used approach to measure flow harmonics, which efficiently suppresses the non-flow correlations, is the multi-particle cumulant method [21, 22]. In this method, the 2k-particle azimuthal correlations, corrm_{k}(2k), are calculated and then used to obtain the multi-particle cumulants, c_{k}(2k). By definition, 2k-particle cumulants describe genuine 2k-particle correlations, i.e. the correlations between fewer number of particles than 2k, which include most of non-flow correlations, are subtracted.

The cumulative method was used for systems including Pb+Pb, p+Pb and recently pp collisions [23–26]. ATLAS measured multi-particle cumulants in pp collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV, and $\sqrt{s_{NN}} = 5.02$ TeV p+Pb and in low-multiplicity Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8]. To avoid event multiplicity fluctuations, which can mimic the collective-like effects [8, 24], cumulants are calculated in unit-size bins in the number of reference particles, M$_{ref}$, which is defined as the number of reconstructed charged particles with $|\eta| < 2.5$ and with p$_T$ range: 0.3 $< p_T < 3$ GeV or 0.5 $< p_T < 5$ GeV. The cumulants are then calculated in broader, statistically significant multiplicity intervals by averaging with weights corresponding to the total number of 2k-multiplets in M$_{ref}$ bins and accounting for the event trigger efficiency [8, 22]. Results obtained for different collision systems or p$_T$-ranges

![Figure 6](image1.png)

**Figure 6.** The second order cumulant c$_2^4(4)$ obtained from four-particle correlations as a function of $\langle N_{ch}(p_T > 0.4 \text{ GeV}) \rangle$ for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8].

![Figure 7](image2.png)

**Figure 7.** Comparison of v$_2^2(2, |\Delta\eta| > 2)$, v$_2^4(4)$, v$_2^6(6)$ and v$_2^8(8)$ as a function of $\langle N_{ch}(p_T > 0.4 \text{ GeV}) \rangle$ for $\sqrt{s_{NN}} = 5.02$ TeV p+Pb collisions and $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions. The results are presented for particles with 0.3 $< p_T < 3$ GeV[8].
are compared in a common event activity variable, $N_{ch}(p_T > 0.4)$, defined as the mean number of charged particles with $p_T > 0.4$ GeV in events in the $M_{ref}$ interval used for the cumulant calculations.

Figure 6 shows the four-particle cumulants measurement in $pp$ collisions at $\sqrt{s} = 5.02$ and $13$ TeV, $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $0.3 < p_T < 3$ GeV. One can see that they follow the ordering $|c_2[4]|_{p+Pb} < |c_2[4]|_{Pb+Pb}$ for $N_{ch}(p_T > 0.4$ GeV$)>100$. Therefore, the magnitude of the corresponding elliptic flow, $v_2[4] = \sqrt{-c_2[4]}$, is larger for $Pb+Pb$ collisions than for $p+Pb$ events. For $5.02$ TeV $pp$ collisions, the $c_2[4]$ cumulants are positive or consistent with zero over the full range of particle multiplicities. For the $13$ TeV $pp$ data, the cumulants are positive over the large range of multiplicities, with the exception of $N_{ch}$ from 130 to 150, where $c_2[4]$ is smaller than zero within 1–2 standard deviations. Therefore, these measurements of positive $c_2[4]$ cumulants in $pp$ collisions do not allow to calculate the Fourier harmonics.

Figure 7 shows a comparison of the $v_2[2, |\Delta \eta| > 2]$ harmonics calculated with the requirement of pseudorapidity separation $|\Delta \eta| > 2$, $v_2[4]$, $v_2[6]$ and $v_2[8]$, for $p+Pb$ and low-multiplicity $Pb+Pb$ collisions. All derived $v_2$ harmonics have larger magnitudes in $Pb+Pb$ collisions than in $p+Pb$ collisions with the same multiplicity. For both systems for $N_{ch}$ above 100, $v_2[2k]$ are similar for $k = 2, 3$ and 4 while $v_2[2, |\Delta \eta| > 2]$ is systematically larger than the harmonics $v_2[2k]$ calculated with more than two-particle cumulants due to fluctuations in the initial-state geometry [28].

5 Subevent cumulant method

To further reduce the non-flow correlations, especially in $pp$ collisions and low-multiplicity $p+Pb$ collisions, ATLAS has developed an improved cumulant method based on the correlations between particles from different subevents separated in pseudorapidity [9]. In particular, correlating particles from two subevents constructed of particles with $\eta < 0$ (subevent $a$) and $\eta > 0$ (subevent $b$) suppresses non-flow contribution mainly from short-range correlations, like correlations within jets, while in the case of three-subevents correlating particles from subevent $b$ of $|\eta| < 0.833$ with particles from subevents $a$ of $\eta < -0.833$ and $c$ of $\eta > 0.833$, additionally lowers contribution from dijets. The capability of the subevent cumulant method was verified with $\text{PYTHIA} 8$ event generator [27].

Figure 8. The $c_2[4]$ values calculated for charged particles with $0.3 < p_T < 3$ GeV compared for the three cumulant methods from the $13$ TeV $pp$ data. The event averaging is performed for $N_{ch}^{sel}$ calculated for the same $p_T$ range, which is then mapped to $N_{ch}$, the average number of charged particles with $p_T > 0.4$ GeV. The dashed line indicates the $c_2[4]$ value corresponding to a $4\%$ $v_2$ signal [9].
Using the novel, template fitting two-particle correlation method, \( v_n \) \( (n = 2, 3, 4) \) harmonics were measured as a function of multiplicity and transverse momentum in \( pp \) collisions at \( \sqrt{s} = 5.02 \text{ TeV} \) and \( 13 \text{ TeV} \). As a function of the number of charged particles, \( N_{ch} \), the \( v_n \) values are larger than the \( pp \) values at lower multiplicities. The \( p+Pb \) \( v_2 \) values are also larger than the \( pp \) values and increase with \( N_{ch} \).
function of multiplicity, the $v_2$ harmonics in $p+Pb$ at $\sqrt{s_{NN}} = 5.02$ TeV and 8.16 TeV are consistent within the measurement uncertainty. As a function of $p_T$, the $p+Pb$ $v_2$ harmonics are larger than $v_2$ in $pp$ collisions, but a similar dependence on the transverse momentum is seen, which also resembles the trend observed in Pb+Pb collisions.

The two-particle correlation template fitting method was also used to obtain $v_2$ of heavy flavor muons of $4 < p_T^\mu < 8$ GeV in $p+Pb$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The muon-$v_2$ harmonic is found to be constant as a function of multiplicity, while as a function of the transverse momentum a decrease of muon-$v_2$ is observed with increasing $p_T$.

Multi-particle cumulants were measured for $pp$ at $\sqrt{s} = 5.02$ TeV and 13 TeV as well as for $p+Pb$ at $\sqrt{s_{NN}} = 5.02$ TeV collisions and low-multiplicity Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The collective nature of multi-particle correlations is well confirmed for $p+Pb$ and Pb+Pb collisions for charged-particle multiplicities above 100. The measured $v_2$ harmonics from multi-particle cumulants have larger values for Pb+Pb collisions as compared to $p+Pb$ collisions and are similar for both systems at $N_{ch} > 100$ for $k = 2, 3$ and 4, while $v_2[2,|\Delta\eta| > 2]$ is systematically larger than the $v_2[2k]$ calculated with more than two-particle cumulants. This observation is consistent with models assuming fluctuation-driven initial-state anisotropies. For $pp$ collisions, the four-particle cumulants are positive or consistent with zero over the full range of particle multiplicities, with the exception for 13 TeV $pp$ collisions of $N_{ch}$ from 130 to 150, where $c_2(4)$ is smaller than zero within 1–2 standard deviations. Therefore, these measurements in $pp$ collisions, do not satisfy the requirement of being negative for the $v_2[4]$ harmonic calculation since are biased by non-flow contaminations.

Recently, ATLAS has proposed a novel sub-event method for the $c_2[4]$ cumulant measurement, in which particles from different sub-events separated in pseudorapidity are used for cumulant calculations. Monte Carlo simulations show that the subevent cumulant method efficiently suppresses non-flow effects. Clearly negative sign of the four-particle subevent cumulants, $c_2(4)$, allow for flow harmonics calculations both in $pp$ and $p+Pb$ collisions. The $v_2[4]$ harmonics in $pp$ collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV and in $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV are observed to be approximately independent of $N_{ch}$ and lower than the two-particle correlation results. These measurements allow studying the fluctuations in the initial-state geometry of small collision systems.
The measurements of two- and multi-particle correlations presented in this report significantly contribute to the understanding of collectivity in small systems and help to constrain the theoretical modelling.

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**References**